CSE 153
Design of Operating Systems

Fall 18

Lecture 11: Page Replacement

Mapped Files

- Mapped files enable processes to do file I/O using loads and stores
  - Instead of "open, read into buffer, operate on buffer, …"
- Bind a file to a virtual memory region (mmap() in Unix)
  - PTEs map virtual addresses to physical frames holding file data
  - Virtual address base + N refers to offset N in file
- Initially, all pages mapped to file are invalid
  - OS reads a page from file when invalid page is accessed
  - OS writes a page to file when evicted, or region unmapped
  - If page is not dirty (has not been written to), no write needed
    - » Another use of the dirty bit in PTE

Memory Management

- Memory management systems
  - Physical and virtual addressing; address translation
  - Techniques: Partitioning, paging, segmentation
  - Page table size, TLBs, VM tricks

- Policies
  - Page replacement algorithms (3)

Demand Paging (OS)

- We use demand paging (similar to other caches):
  - Pages loaded from disk when referenced
  - Pages may be evicted to disk when memory is full
  - Page faults trigger paging operations
- What is the alternative to demand paging?
  - Some kind of prefetching
- Lazy vs. aggressive policies in systems

Demand Paging (Process)

- Demand paging when a process first starts up
- When a process is created, it has
  - A brand new page table with all valid bits off
  - No pages in memory
- When the process starts executing
  - Instructions fault on code and data pages
  - Faulting stops when all necessary code and data pages are in memory
  - Only code and data needed by a process needs to be loaded
  - This, of course, changes over time…

Page Replacement

- When a page fault occurs, the OS loads the faulted page from disk into a page frame of memory
- At some point, the process has used all of the page frames it is allowed to use
  - This is likely (much) less than all of available memory
- When this happens, the OS must replace a page for each page faulted in
  - It must evict a page to free up a page frame
  - Written back only if it is has been modified (i.e., “dirty”)!

Page replacement policy

- What we discussed so far (page faults, swap, page table structures, etc…) is mechanisms
- Page replacement policy: determine which page to remove when we need a victim
- Does it matter?
  - Yes! Page faults are super expensive
  - Getting the number down, can improve the performance of the system significantly

Considerations

- Page replacement support has to be simple during memory accesses
  - They happen all the time, we cannot make that part slow
- But it can be complicated/expensive when a page fault occurs – why?
  - Reason 1: if we are successful, this will be rare
  - Reason 2: when it happens we are paying the cost of I/O
    - » I/O is very slow: can afford to do some extra computation
    - » Worth it if we can save some future page faults
- What makes a good page replacement policy?

Locality to the Rescue

- Recall that virtual memory works because of locality
  - Temporal and spatial
  - Work at different scales: for cache, at a line level, for VM, at page level, and even at larger scales

- All paging schemes depend on locality
  - What happens if a program does not have locality?
  - High cost of paging is acceptable, if infrequent
  - Processes usually reference pages in localized patterns, making paging practical

Evicting the Best Page

- Goal is to reduce the page fault rate
- The best page to evict is the one never touched again
  - Will never fault on it
- Never is a long time, so picking the page closest to "never" is the next best thing
  - Evicting the page that won't be used for the longest period of time minimizes the number of page faults
  - Proved by Belady
- We're now going to survey various replacement algorithms, starting with Belady's

Belady's Algorithm

- Belady's algorithm
  - Idea: Replace the page that will not be used for the longest time in the future
  - Optimal? How would you show?
  - Problem: Have to predict the future
- Why is Belady's useful then?
  - Use it as a yardstick/upper bound
  - Compare implementations of page replacement algorithms with the optimal to gauge room for improvement
    - » If optimal is not much better, then algorithm is pretty good
  - What's a good lower bound?
    - » Random replacement is often the lower bound

First-In First-Out (FIFO)

- FIFO is an obvious algorithm and simple to implement
  - Maintain a list of pages in order in which they were paged in
  - On replacement, evict the one brought in longest time ago
- Why might this be good?
  - Maybe the one brought in the longest ago is not being used
- Why might this be bad?
  - Then again, maybe it's not
  - We don't have any info to say one way or the other
- FIFO suffers from "Belady's Anomaly"
  - The fault rate might actually increase when the algorithm is given more memory (very bad)

Least Recently Used (LRU)

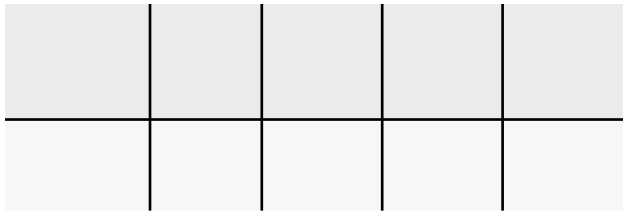
- LRU uses reference information to make a more informed replacement decision
  - Idea: We can't predict the future, but we can make a guess based upon past experience
  - On replacement, evict the page that has not been used for the longest time in the past (Belady's: future)
  - When does LRU do well? When does LRU do poorly?
- Implementation
  - To be perfect, need to time stamp every reference (or maintain a stack) – much too costly
  - So we need to approximate it

Approximating LRU

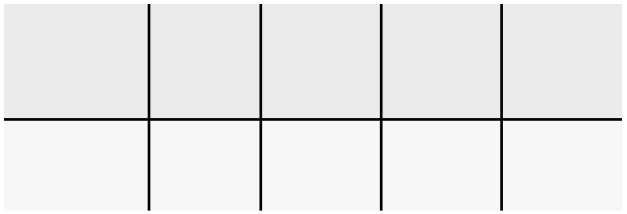
- LRU approximations use the PTE reference bit
  - Keep a counter for each page
  - At regular intervals, for every page do:
    - » If ref bit = 0, increment counter
    - » If ref bit = 1, zero the counter
    - » Zero the reference bit
  - The counter will contain the number of intervals since the last reference to the page
  - The page with the largest counter is the least recently used
- Some architectures don't have a reference bit
  - Can simulate reference bit using the valid bit to induce faults

LRU Approximation

Reference bits



LRU counter

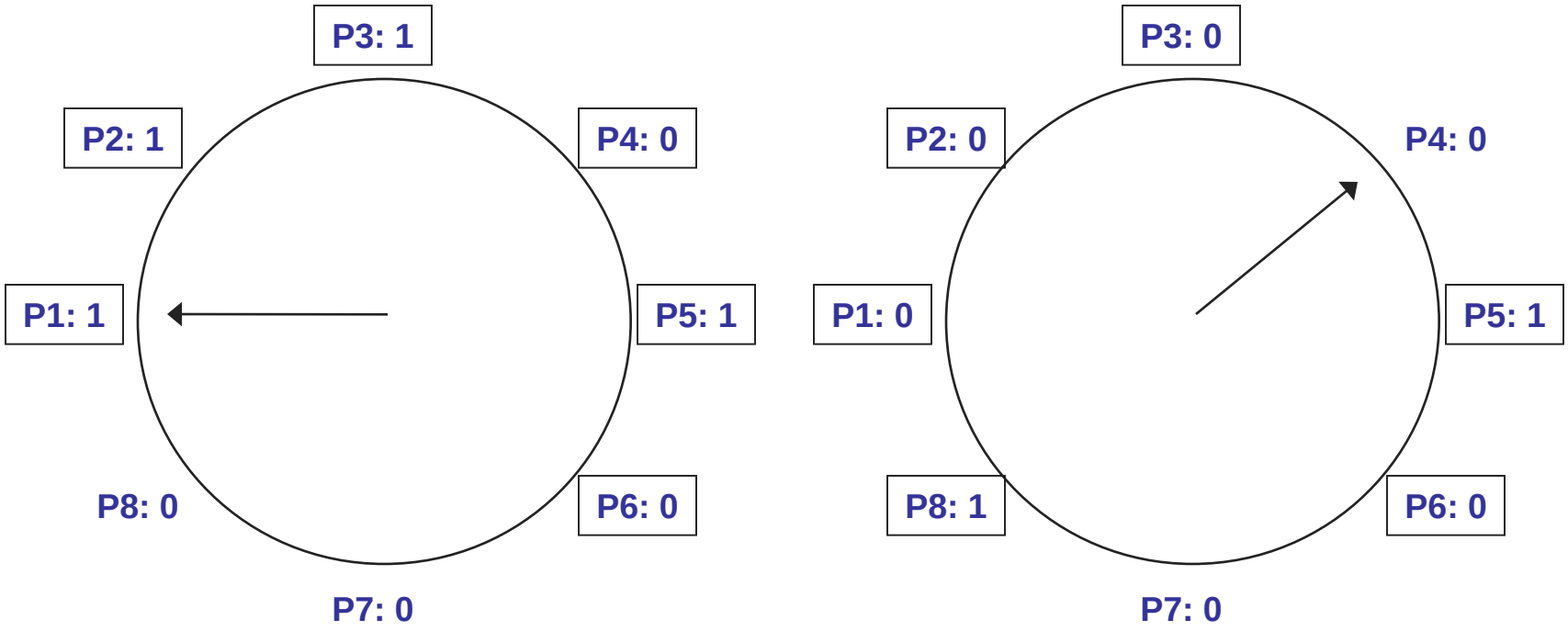


Problem: Overhead of one counter value per page

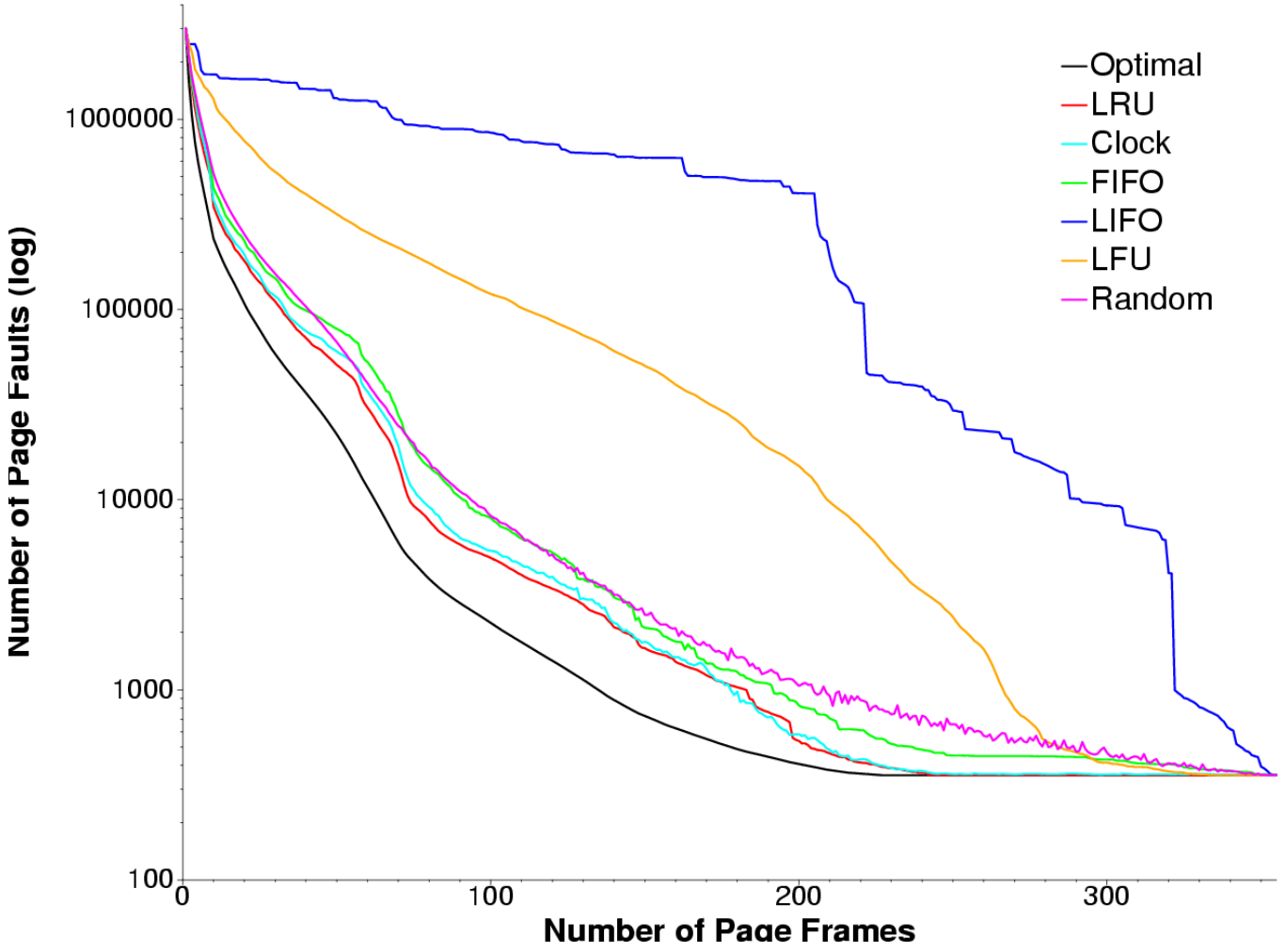
LRU Clock (Not Recently Used)

- Not Recently Used (NRU) – Used by Unix
  - Replace page that is "old enough"
  - Arrange all of physical page frames in a big circle (clock)
  - A clock hand is used to select a good LRU candidate
    - » Sweep through the pages in circular order like a clock
    - » If the ref bit is off, it hasn't been used recently
      - What is the minimum "age" if ref bit is off?
    - » If the ref bit is on, turn it off and go to next page
  - Arm moves quickly when pages are needed
  - Low overhead when plenty of memory
  - If memory is large, "accuracy" of information degrades
    - » What does it degrade to?
    - » One fix: use two hands (leading erase hand, trailing select hand)

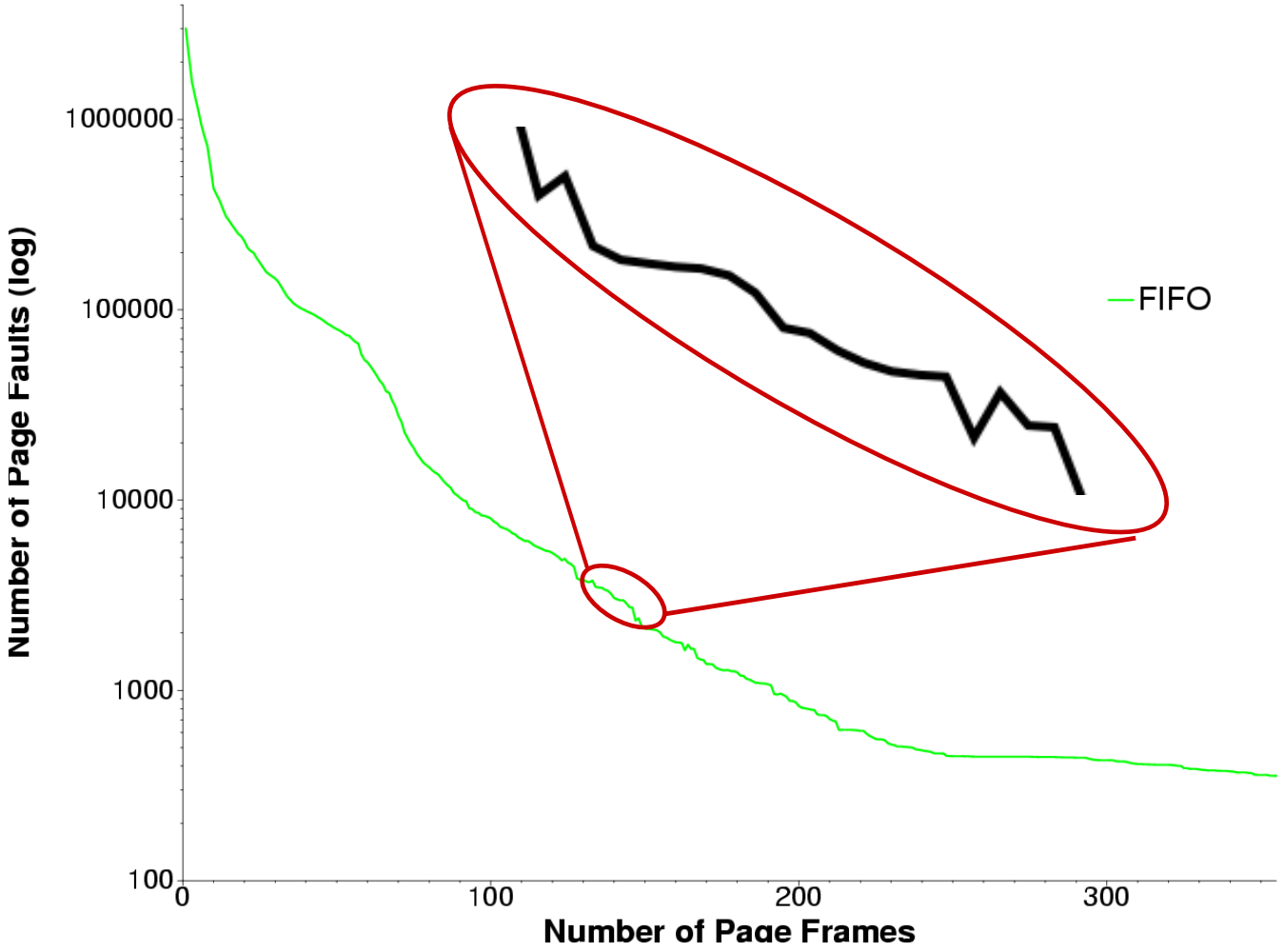
LRU Clock



Example: gcc Page Replace



Example: Belady's Anomaly



Other ideas

- Victim buffer
  - Add a buffer (death row!) we put a page on when we decide to replace it
  - Buffer is FIFO
  - If you get accessed while on death row – clemency!
  - If you are the oldest page on death row – replacement!

Fixed vs. Variable Space

- In a multiprogramming system, we need a way to allocate memory to competing processes
- Problem: How to determine how much memory to give to each process?
  - Fixed space algorithms
    - » Each process is given a limit of pages it can use
    - » When it reaches the limit, it replaces from its own pages
    - » Local replacement
      - Some processes may do well while others suffer
  - Variable space algorithms
    - » Process' set of pages grows and shrinks dynamically
    - » Global replacement
      - One process can ruin it for the rest

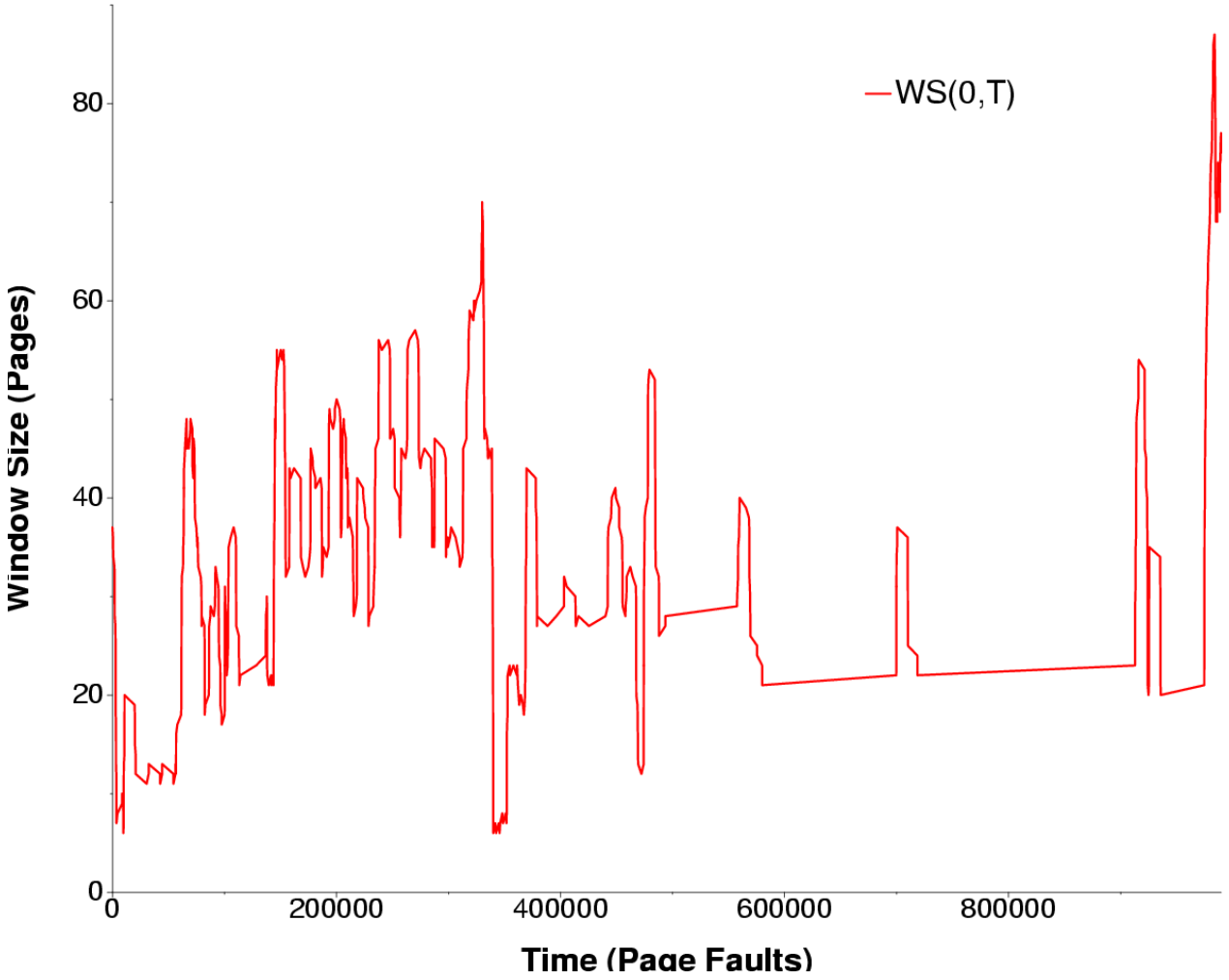
Working Set Model

- A working set of a process is used to model the dynamic locality of its memory usage
  - Defined by Peter Denning in 60s
- Definition
  - WS(t,w) = {set of pages P, such that every page in P was referenced in the time interval (t, t-w)}
  - t – time, w – working set window (measured in page refs)
- A page is in the working set (WS) only if it was referenced in the last w references

Working Set Size

- The working set size is the number of pages in the working set
  - The number of pages referenced in the interval (t, t-w)
- The working set size changes with program locality
  - During periods of poor locality, you reference more pages
  - Within that period of time, the working set size is larger
- Intuitively, want the working set to be the set of pages a process needs in memory to prevent heavy faulting
  - Each process has a parameter w that determines a working set with few faults
  - Denning: Don't run a process unless working set is in memory

Example: gcc Working Set



Working Set Problems

- Problems
  - How do we determine w?
  - How do we know when the working set changes?
- Too hard to answer
  - So, working set is not used in practice as a page replacement algorithm
- However, it is still used as an abstraction
  - The intuition is still valid
  - When people ask, “How much memory does Firefox need?”, they are in effect asking for the size of Firefox’s working set

Page Fault Frequency (PFF)

- Page Fault Frequency (PFF) is a variable space algorithm that uses a more ad-hoc approach
  - Monitor the fault rate for each process
  - If the fault rate is above a high threshold, give it more memory
    - So that it faults less
    - But not always (FIFO, Belady's Anomaly)
  - If the fault rate is below a low threshold, take away memory
    - Should fault more
    - But not always
- Hard to use PFF to distinguish between changes in locality and changes in size of working set

Thrashing

- Page replacement algorithms avoid thrashing
  - When most of the time is spent by the OS in paging data back and forth from disk
  - No time spent doing useful work (making progress)
  - In this situation, the system is overcommitted
    - » No idea which pages should be in memory to reduce faults
    - » Could just be that there isn't enough physical memory for all of the processes in the system
    - » Ex: Running Windows95 with 4 MB of memory…
  - Possible solutions
    - » Swapping – write out all pages of a process
    - » Buy more memory

Summary

- Page replacement algorithms
  - Belady's – optimal replacement (minimum # of faults)
  - FIFO – replace page loaded furthest in past
  - LRU – replace page referenced furthest in past
    - » Approximate using PTE reference bit
  - LRU Clock – replace page that is "old enough"
  - Working Set – keep the set of pages in memory that has minimal fault rate (the "working set")
  - Page Fault Frequency – grow/shrink page set as a function of fault rate
- Multiprogramming
  - Should a process replace its own page, or that of another?